AEDC-TR-77-119

Cy. 2

INFRARED SOURCE TO SIMULATE EARTH-LIMB BACKGROUND

Willis L. Clark
ARO, Inc., a Sverdrup Corporation Company

VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

August 1978

Final Report for Period September 5 – 16, 1977

Prepared for

ARNOLD ENGINEERING DEVELOPMENT CENTER/DOTR
ARNOLD AIR FORCE STATION, TENNESSEE 37389

APPROVAL STATEMENT

This report has been reviewed and approved.

Herman E. Scott

HERMAN E. SCOTT
Project Manager, Research Division
Directorate of Test Engineering

Approved for publication:

FOR THE COMMANDER

Robert W. Crossley

ROBERT W. CROSSLEY, Lt Colonel, USAF
Acting Director of Test Engineering
Deputy for Operations

UNCLASSIFIED

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AEDC-TR-77-119	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INFRARED SOURCE TO SIMULATE EARTH-LIMB BACKGROUND		5. TYPE OF REPORT & PERIOD COVERED Final Report-September 5 - 16, 1977
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Willis L. Clark, ARO, Inc.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Arnold Engineering Development Center/DOT Air Force Systems Command Arnold Air Force Station, Tennessee 37389		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 65807F
11. CONTROLLING OFFICE NAME AND ADDRESS Arnold Engineering Development Center/DOS Arnold Air Force Station, Tennessee 37389		12. REPORT DATE August 1978
		13. NUMBER OF PAGES 35
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in DDC

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

test methods	altitude	space environments
earth limb	surveillance	
simulator	gradients	
temperature	heat	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the preliminary design and check out of an earth-limb simulator. The actual simulator will operate in a temperature range from 40°K to 100°K for an altitude range of 60 to 115 km. In order to check the design, temperatures were uniformly elevated for the preliminary testing.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F. The results of the test were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project No. V35S-B5A. Herman E. Scott was the Air Force project manager. The data analysis was completed on September 16, 1977, and the manuscript was submitted for publication on November 7, 1977.

CONTENTS

ILLUSTRATIONS

APPENDIX

1.0 INTRODUCTION

A satellite-borne surveillance sensor scans from outer space to the hard earth in its search for a target. In such a scan, the sensor encounters a thermal gradient which increases as the scan approaches earth. This thermal gradient (which starts with the cold, rarefied gases of the upper atmosphere and continues to the hot, dense gases at sea level) is referred to as the earth-limb thermal gradient. The earth-limb gradient and a typical satellite-borne sensor scan sequence are illustrated in Fig. 1.

The calibration of such a sensor system requires the investigation of phenomena directly attributable to the mission requirements of scanning into the earth-limb region. A sensor viewing a missile through the earth-limb region requires reasonable off-axis rejection to separate the missile from the background radiation of the earth limb. Should the mission require the sensor to scan further down toward hard earth, the sensor will go into full saturation. It is necessary to know where saturation will occur with respect to the viewing altitude.

If the sensor (while in saturation) starts a scan away from hard earth toward outer space it will remain in saturation for some finite period of time. The recovery time is of utmost importance for a surveillance satellite.

An earth-limb simulator concept for use in sensor testing is shown in Fig. 2. The thermal gradient of the earth-limb simulator is projected by the imaging mirror onto a diffuse screen then projected as a collimated beam to fill the entrance aperture of the sensor.

The Optical Signatures Code (OSC) is a large collection of computer programs which predict the radiation emitted by typical targets and backgrounds viewed by long wavelength infrared (LWIR) sensors in ballistic missile defense missions. The programs in the OSC were developed under the sponsorship of the Army's Ballistic Missile Defense Advanced Technology Center, and some are now operational on the Arnold Engineering Development Center (AEDC) central computer. A plot of the spectral radiance at 100-km altitude obtained from the OSC is presented in Fig. 3. The spectral radiance data from the Earth Limb Signatures Code was used to establish the radiation requirements for the earth-limb background simulator.

2.0 DESIGN AND TEST PROCEDURES

A typical LWIR sensor is sensitive to radiation in the 9- to 11-μm band and has a 2.5-deg field of view. Installed in the AEDC von Kármán Gas Dynamics Facility (VKF) Aerospace Chamber (7V) (Chamber 7V), and looking directly at the 28-in. collimating mirror, a 10-in. by 10-in. plate is required at the focal point of the mirror to fill the field of view of the sensor.

The radiance values integrated over the 9- to 11-μm band covering the appropriate altitude range was obtained from the Earth Limb Signatures Code. These values were then substituted into Planck's equation to calculate the black-body temperature required to produce the desired radiance level at each altitude. The temperatures calculated by this procedure were in the 30°K to 100°K range.

This study resulted in the design of a heated plate with a temperature profile to match the temperatures calculated above. The plate was tested at ambient conditions to allow standard temperature measuring techniques and to check calculations used in the mathematical model. The calculated temperatures were elevated to the 32°C to 60°C temperature range, and the resulting temperature profile is shown in Fig. 4.

Using the minimum plate dimensions and the temperature profile, a stainless steel plate of varying thickness which would reproduce the required temperature profile was designed. The design required the derivation of the appropriate heat-transfer equations and boundary conditions for the mathematical model. The mathematical model using the Runge-Kutta integration method is shown in Appendix A.

The design resulted in a plate heated on both ends and varying in thickness as shown in Fig. 6. The calculated heat input was 10.9 watts for the warm end and 5.08 watts for the cool end. These inputs assumed the plate to be under vacuum and radiating to a 21°C heat sink. Figure 5 is the temperature profile of the plate with the given inputs calculated from the method shown in Appendix A.

3.0 RESULTS

When the fabrication of the plate was completed, an IR thermal imaging camera was used to acquire the temperature profiles on the plate. The thermal imaging camera is a television-like scanning system which displays thermal images on a monitor. The camera utilizes a liquid-nitrogen-cooled Indium Antimonide detector which has spectral sensitivity over the 2- to 5.6-μm range. The minimum detectable temperature difference is better than 0.2°C at an object temperature of 30°C. Frames are produced at a rate of 16 per second which corresponds to a line frequency of 1,600 lines per second. The images produced by this system (by remote sensing of infrared radiation) provide instant thermal profiles.

The data acquisition technique was by adjustment of the isothermal contour lines on the output monitor. The controls provide two isothermal contour lines, the temperature difference being measured as the difference between the two isothermal contours. In Fig. 14, the two vertical lines within the green color band are the two isotherm markers. The marker on the left corresponds to the isotherm at the center of the plate indicated by the center arrow. The marker on the right corresponds to the isothermal contour lines indicated by the two arrows on each side of center. Figures 14 through 18 are photographs of the monitor at various temperatures and are typical for the full range of data. Figure 13 is a photograph of the TV monitor output without the isothermal contour lines.

Figures 7, 8, and 9 are the plots of the temperature data for the middle, left, and right sides of the plate along with a plot of the design goal. It can be seen from these figures that the general profile of the temperature was reproduced by the plate. No attempt was made to match the absolute level between the required and acquired data because of the long stabilization time inherent in the plate. More input heat was required than was calculated; however, the test was conducted under ambient conditions rather than under vacuum conditions as used for design calculations.

Figures 10, 11, and 12 are various views of the plate. The shape of the plate can be seen in Fig. 12 and compared to the shape shown graphically in Fig. 6.

4.0 CONCLUSIONS

The general profile of the earth limb was reproduced in a flat plate which now requires only the modification of the input power to be used as a simulator for the low level earth-limb radiation. Further tests should be conducted to determine the effect of various background temperatures, the effect of vacuum conditions on power input and temperature distribution, and possibly the effect of various emissive coatings.

From the data obtained in this check out, the modeling calculations were adequate. Some further refinement may be required to predict the input energy requirements; however, it will require study in a vacuum environment to make these final adjustments to the equations. As shown in the data plots, the shape of the required temperature profile was simulated by the plate. Further study is required to provide a plate with the same contour but with temperatures in the 30°K to 100°K range as required for sensor calibration.

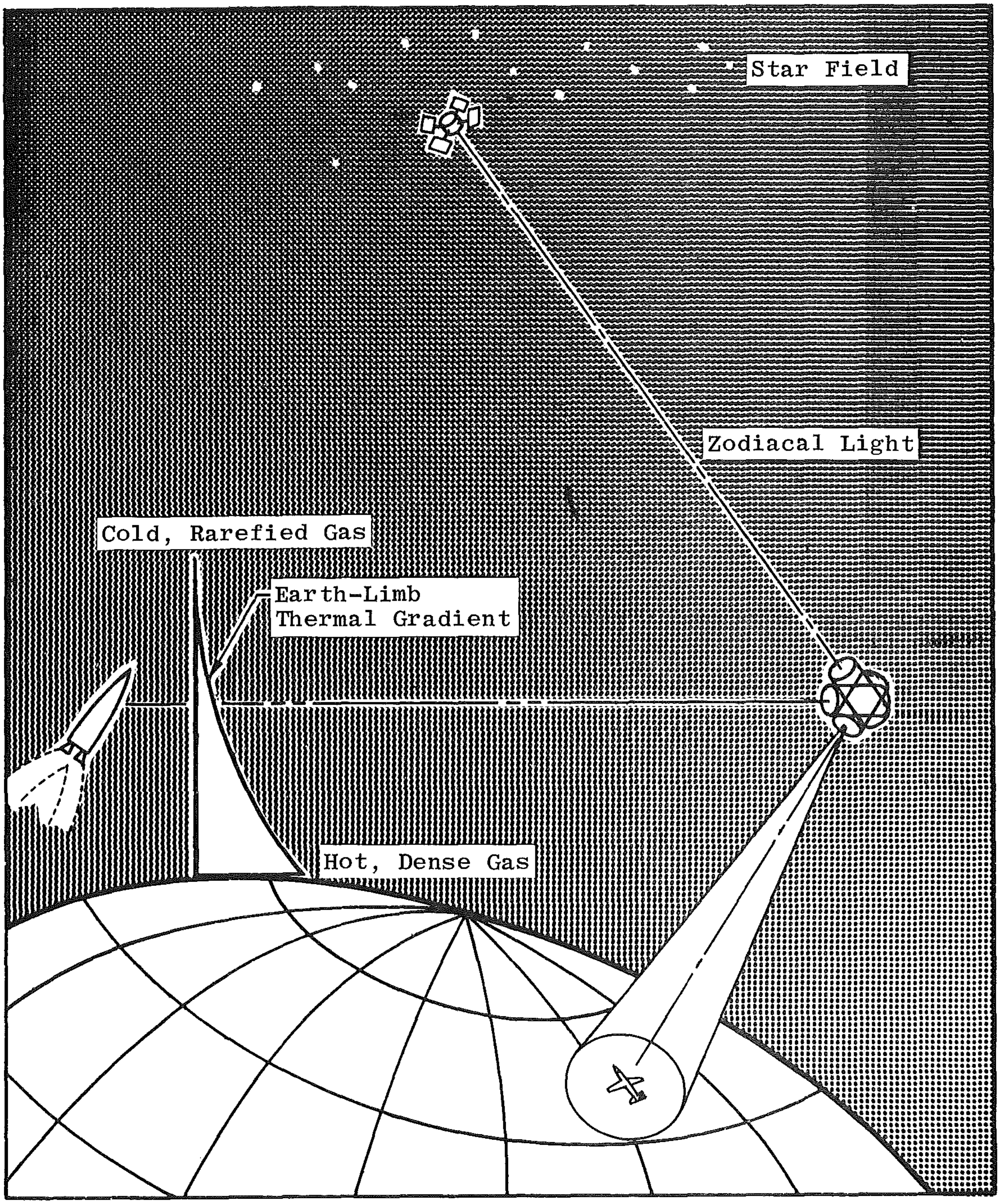


Figure 1. LWIR sensor environment.

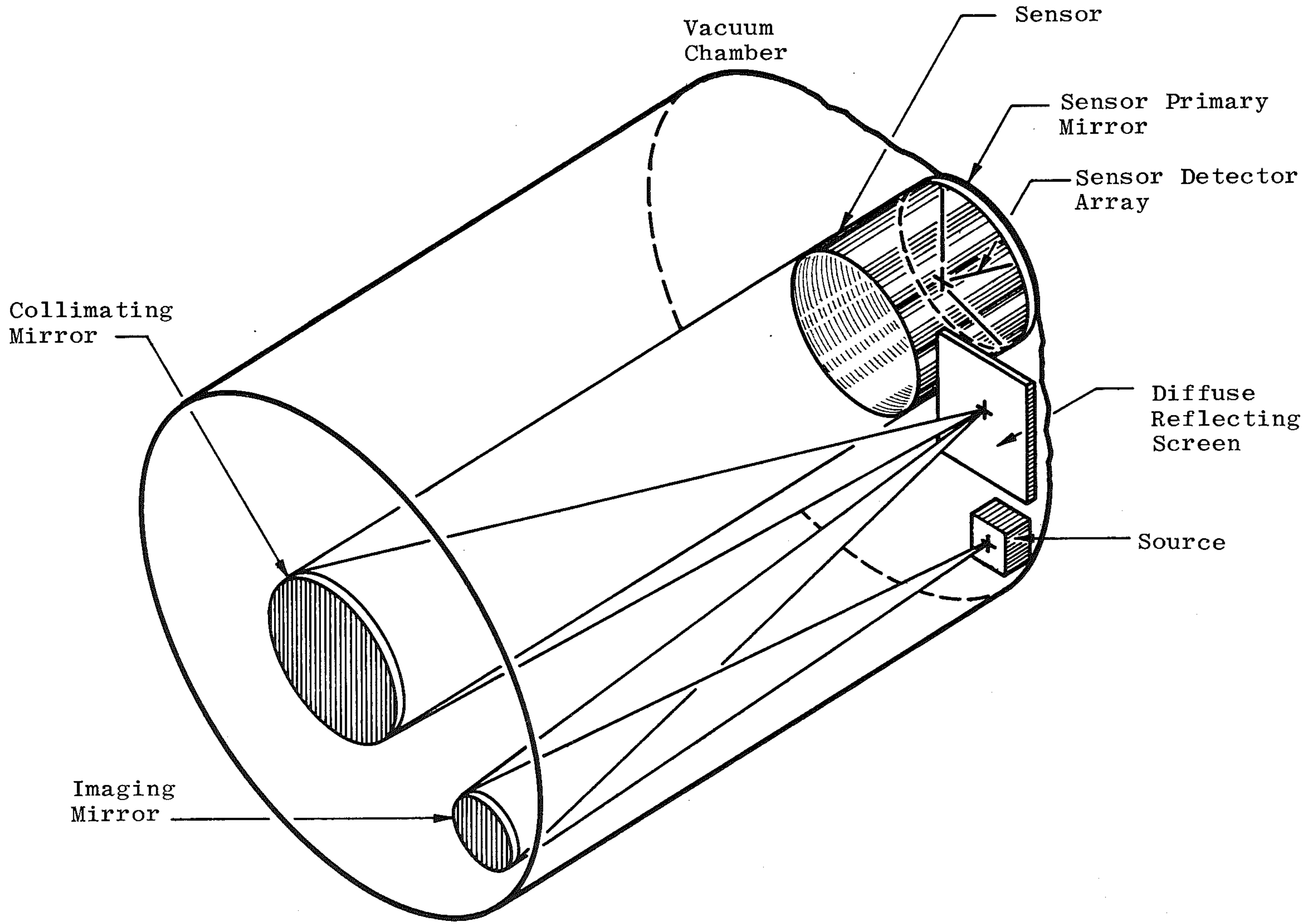


Figure 2. Typical test configuration.

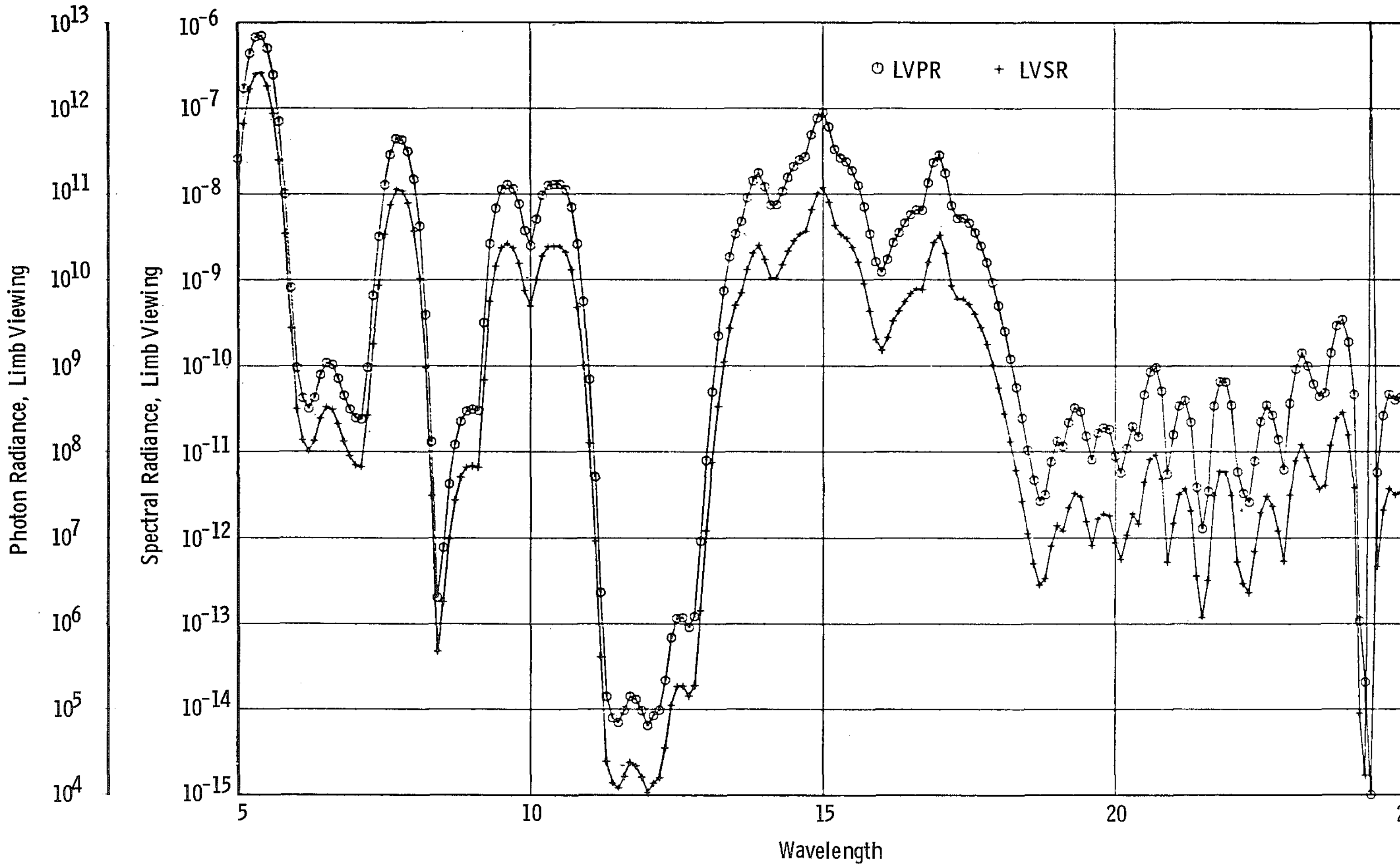


Figure 3. Photon and spectral radiance of earth limb at 100 km.

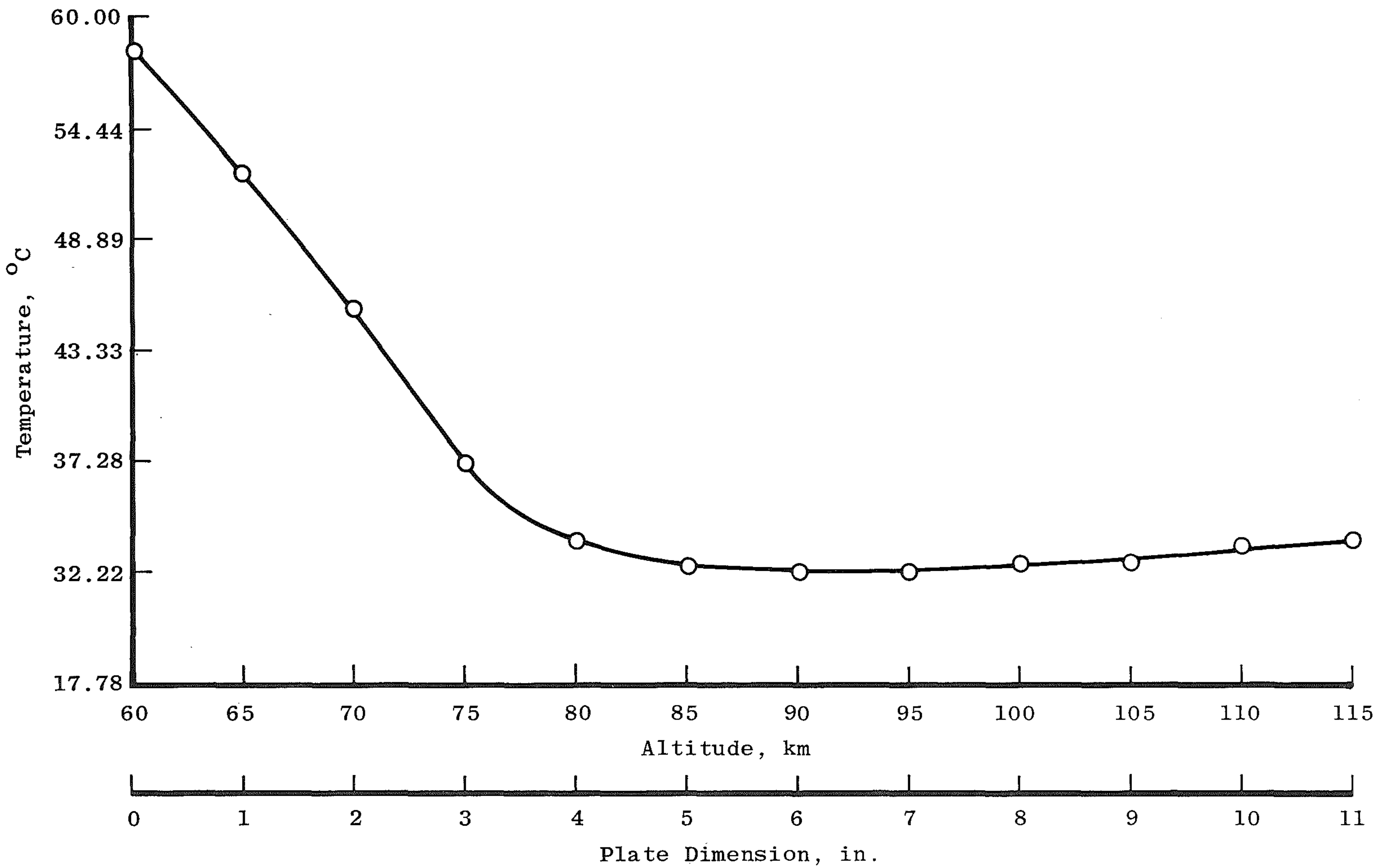


Figure 4. Temperature-altitude curve for earth limb.

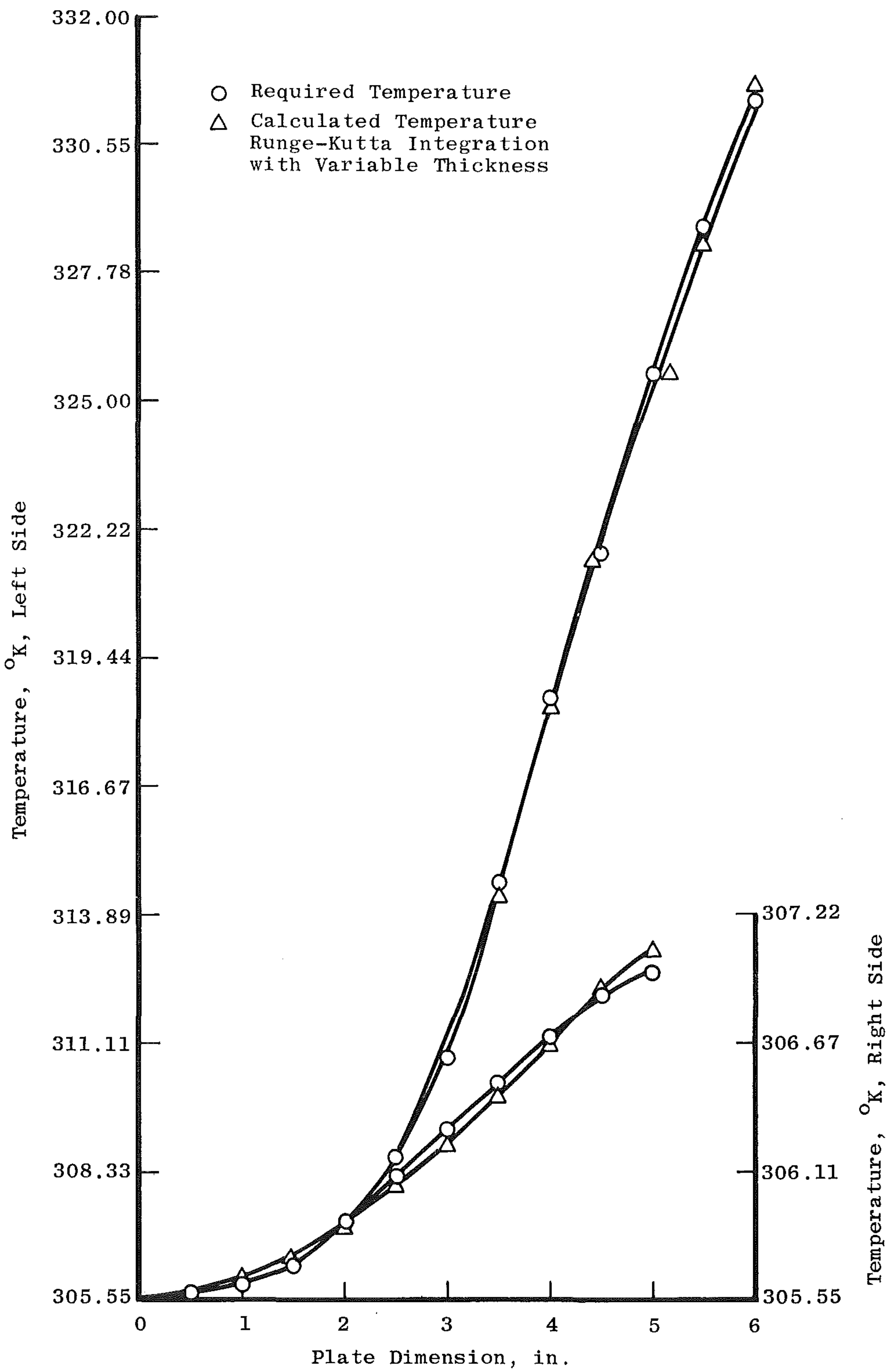


Figure 5. Required plate temperature-plate dimension.

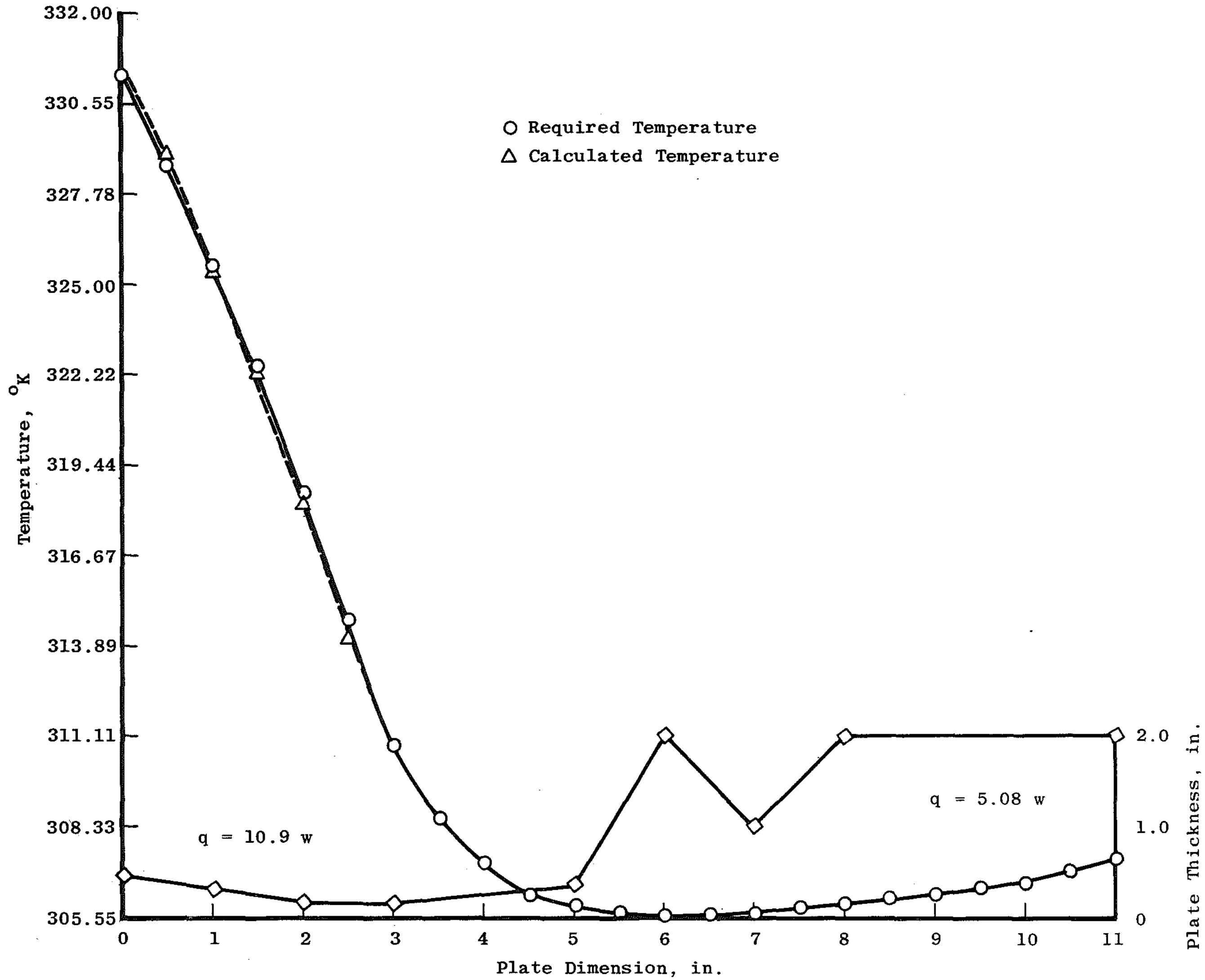


Figure 6. Calculated plate temperature-plate dimension.

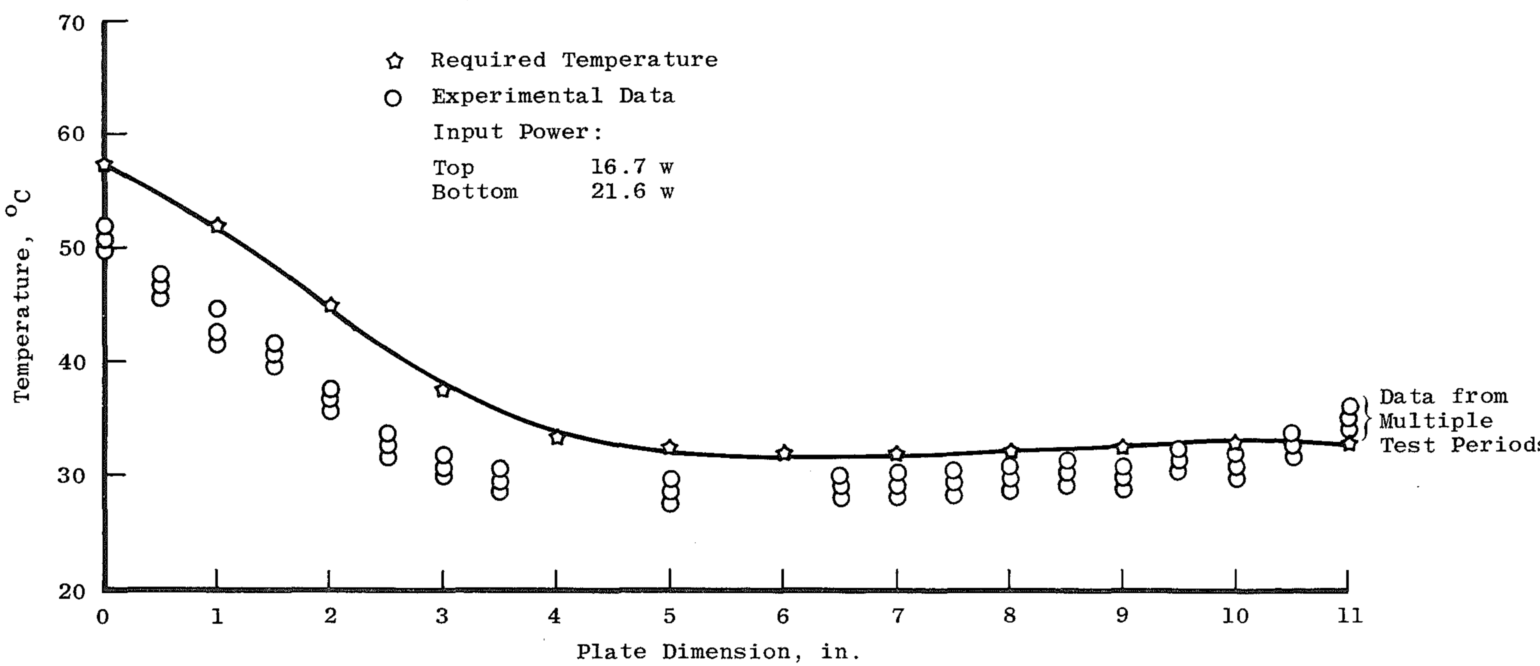


Figure 7. Section of test data through center of plate.

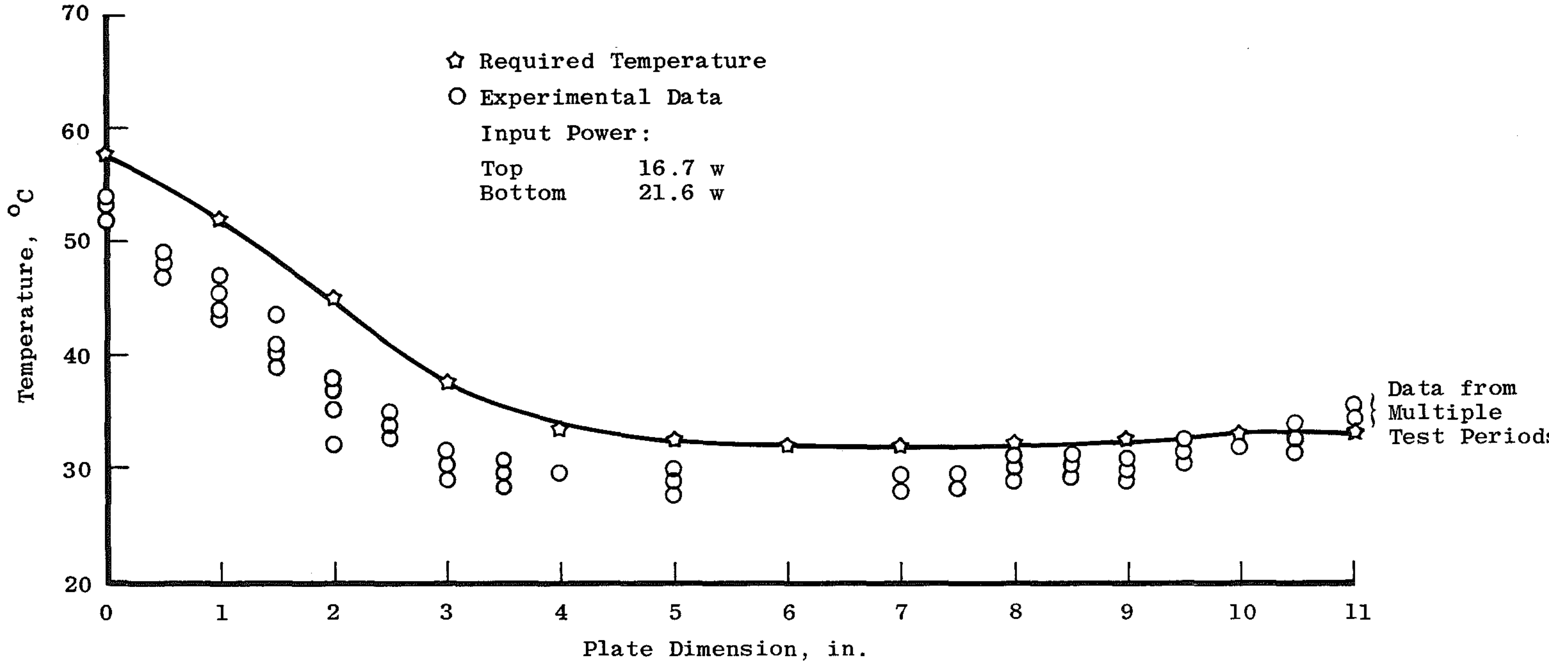


Figure 8. Section of test data at left side of plate.

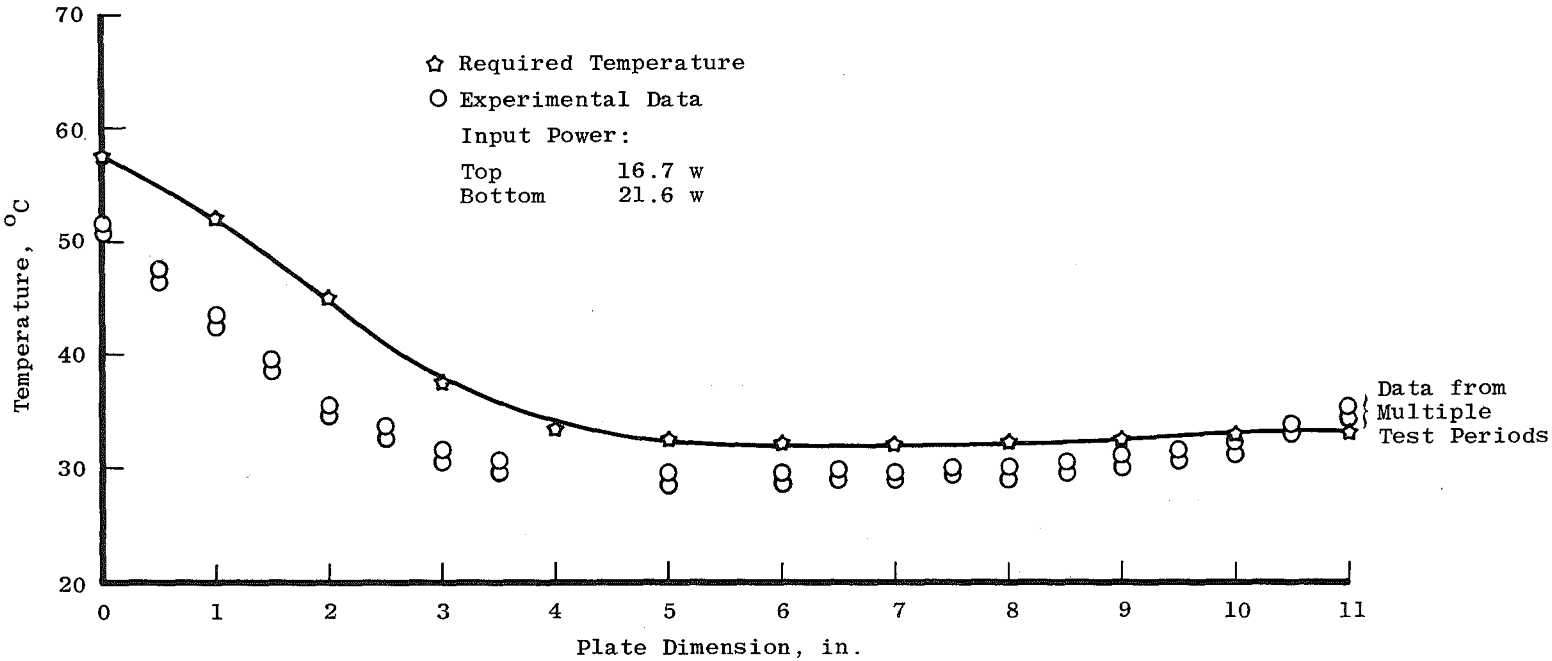


Figure 9. Section of test data at right side of plate.

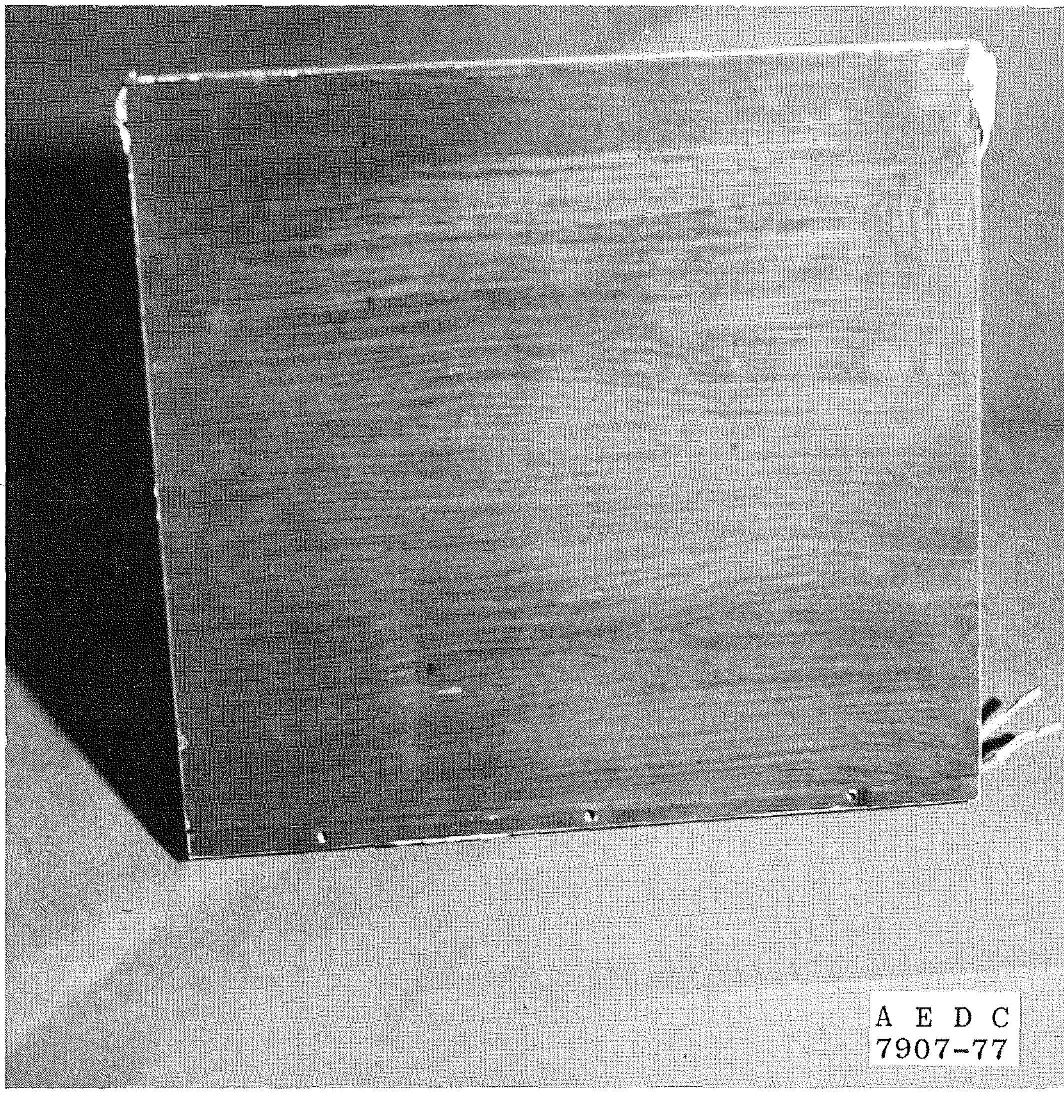


Figure 10. Front view of simulator.

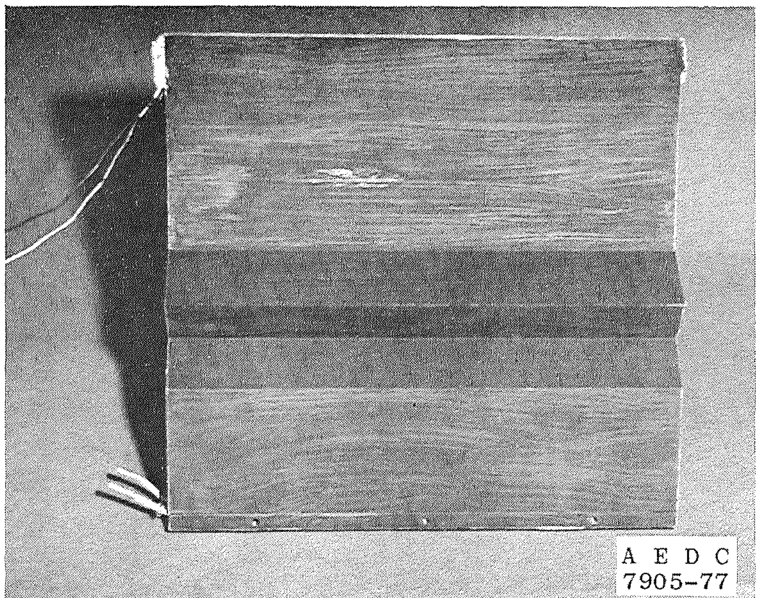


Figure 11. Rear view of simulator.

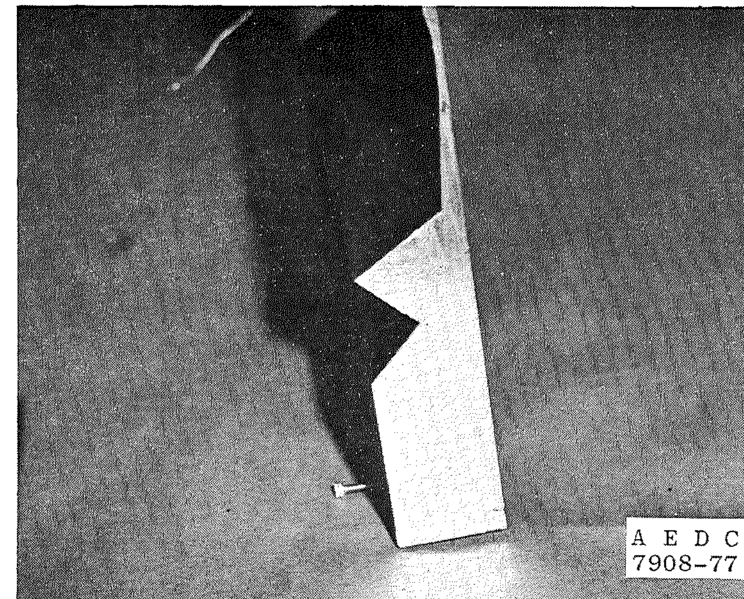


Figure 12. Side view of simulator.

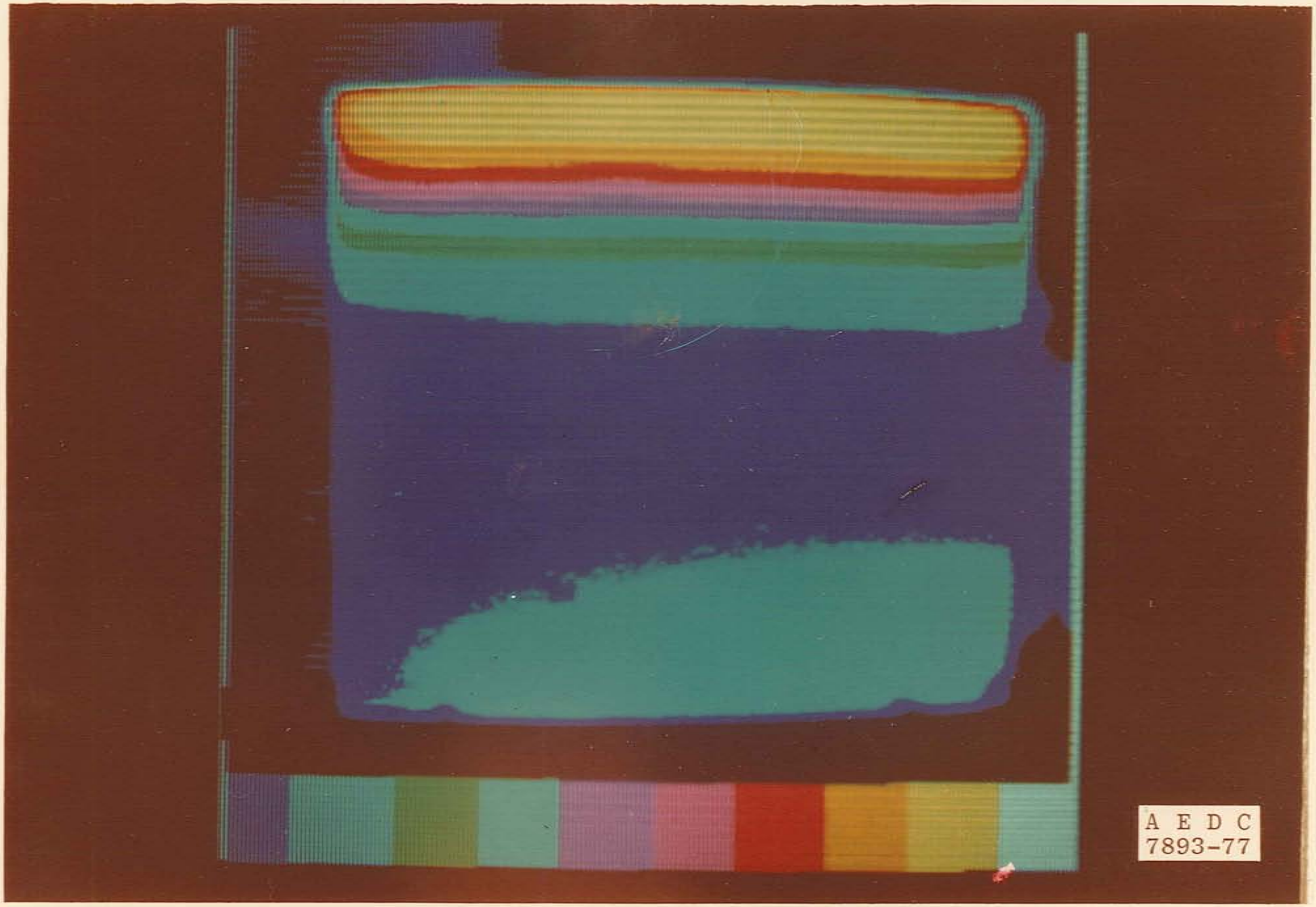


Figure 13. Thermal image of simulator without isothermal contour lines.

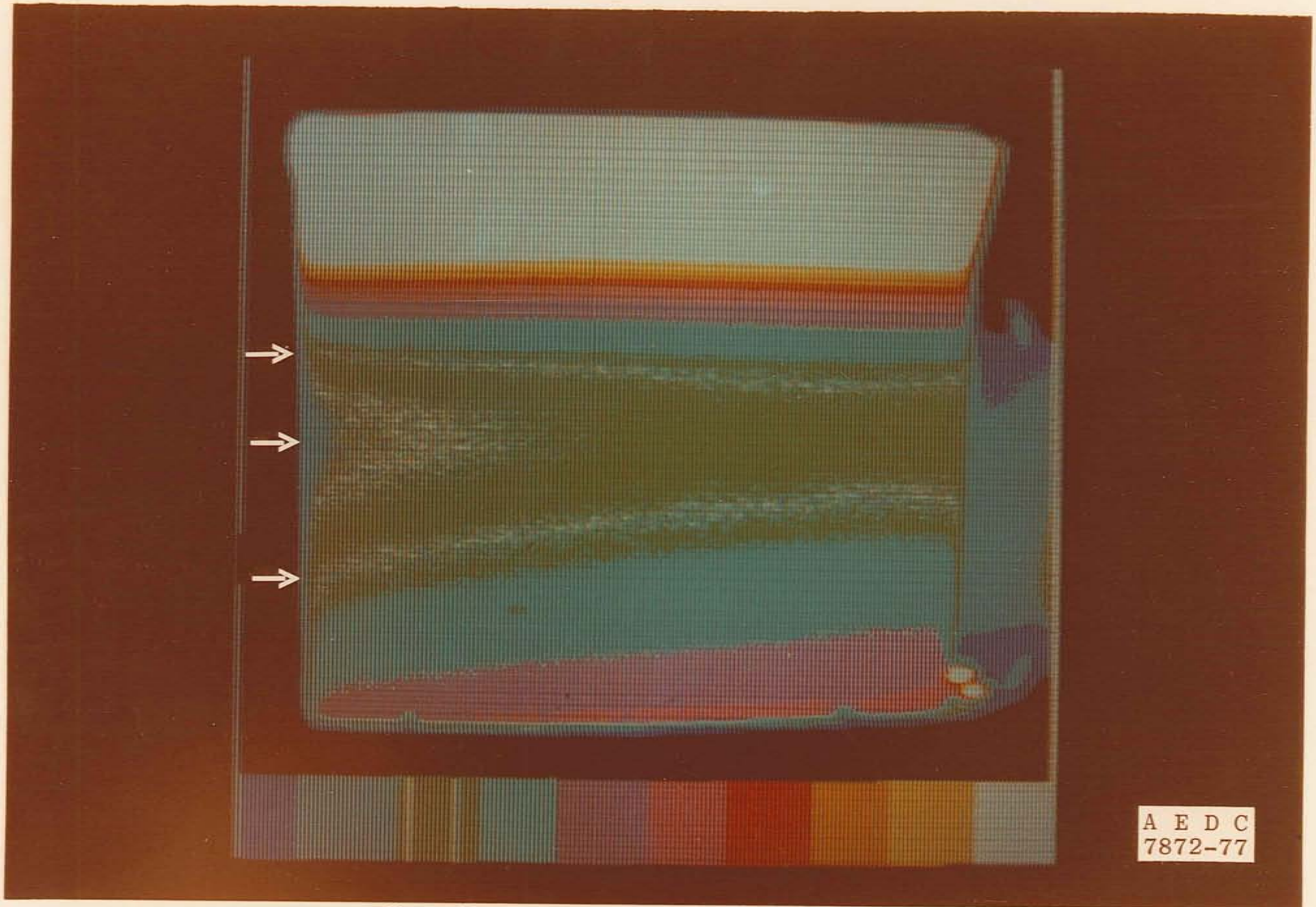


Figure 14. Thermal image of simulator with isothermal contours set at $\Delta T = 1^\circ C$.

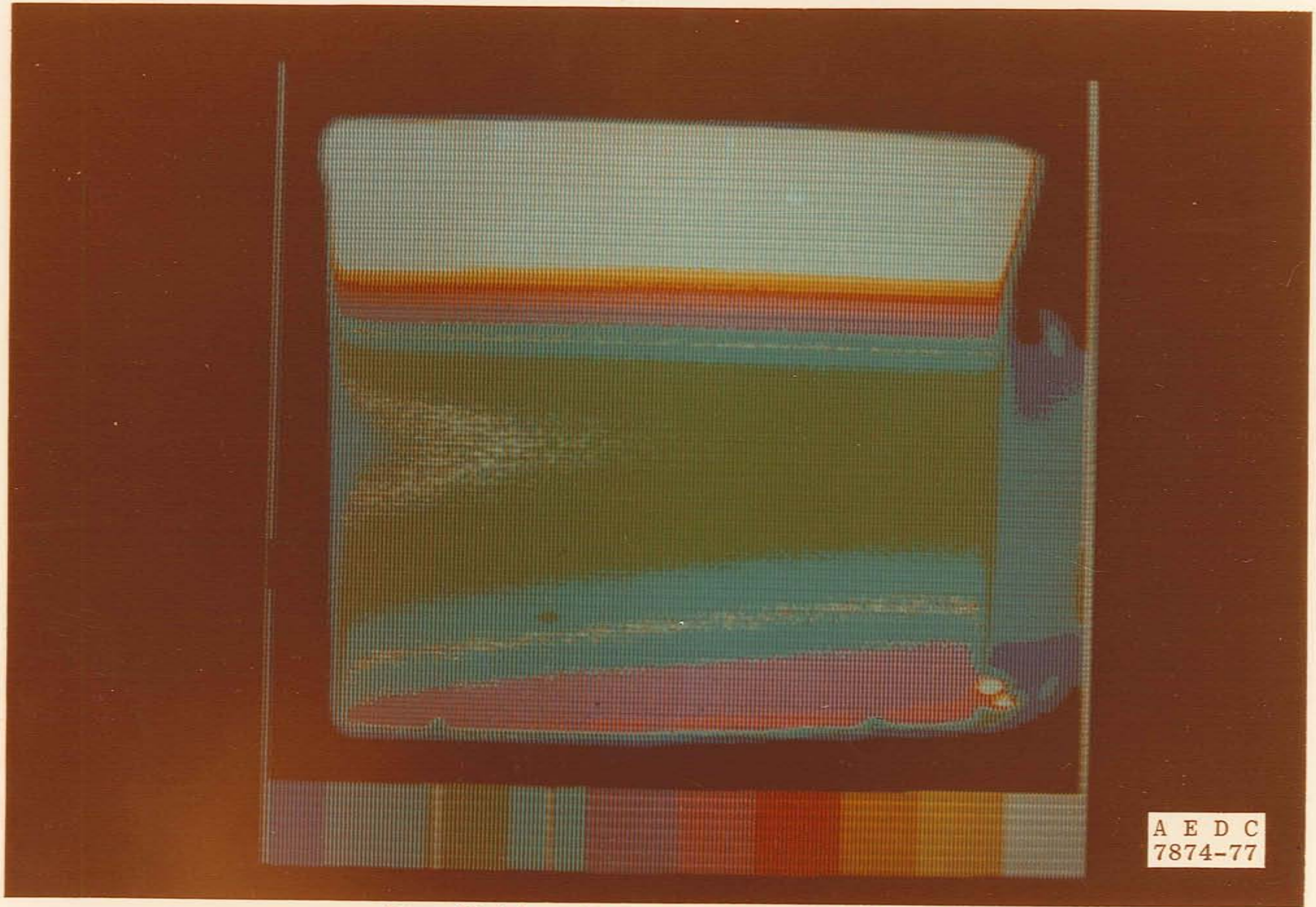


Figure 15. Thermal image of simulator with isothermal contours set at $\Delta T = 2^\circ C$.

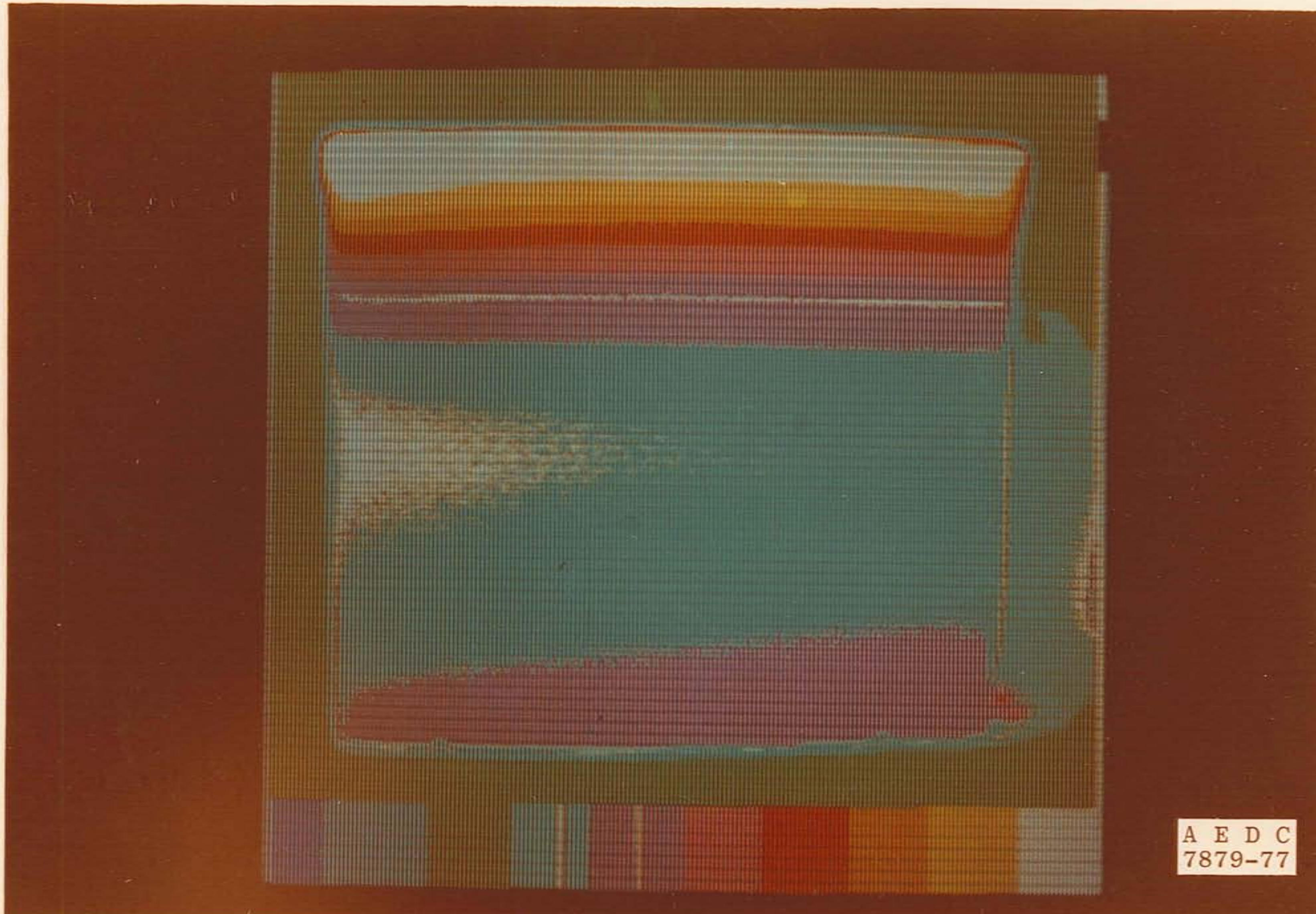


Figure 16. Thermal image of simulator with isothermal contours set at $\Delta T = 10^{\circ}C$.

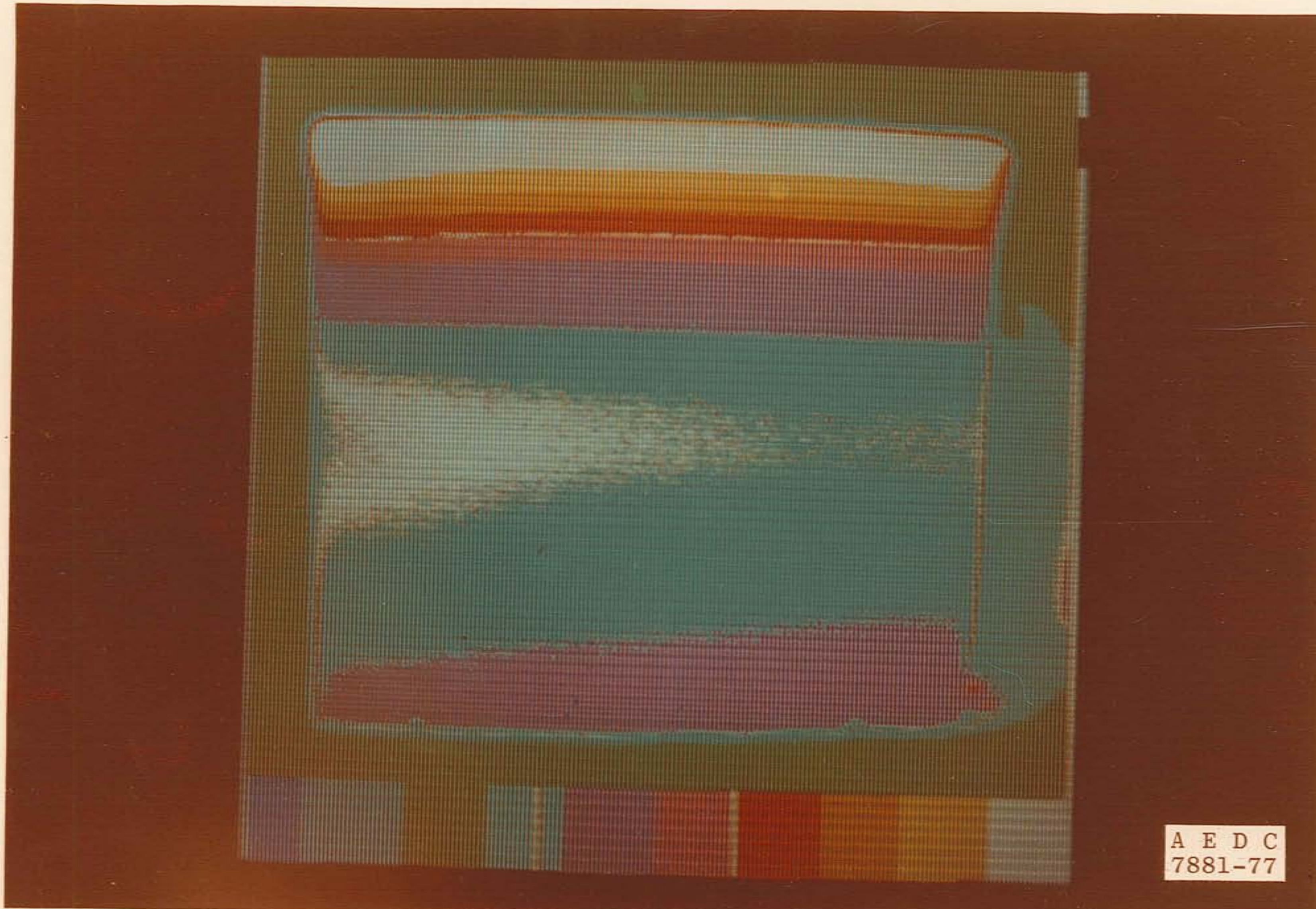


Figure 17. Thermal image of simulator with isothermal contours set at $\Delta T = 20^{\circ}C$.

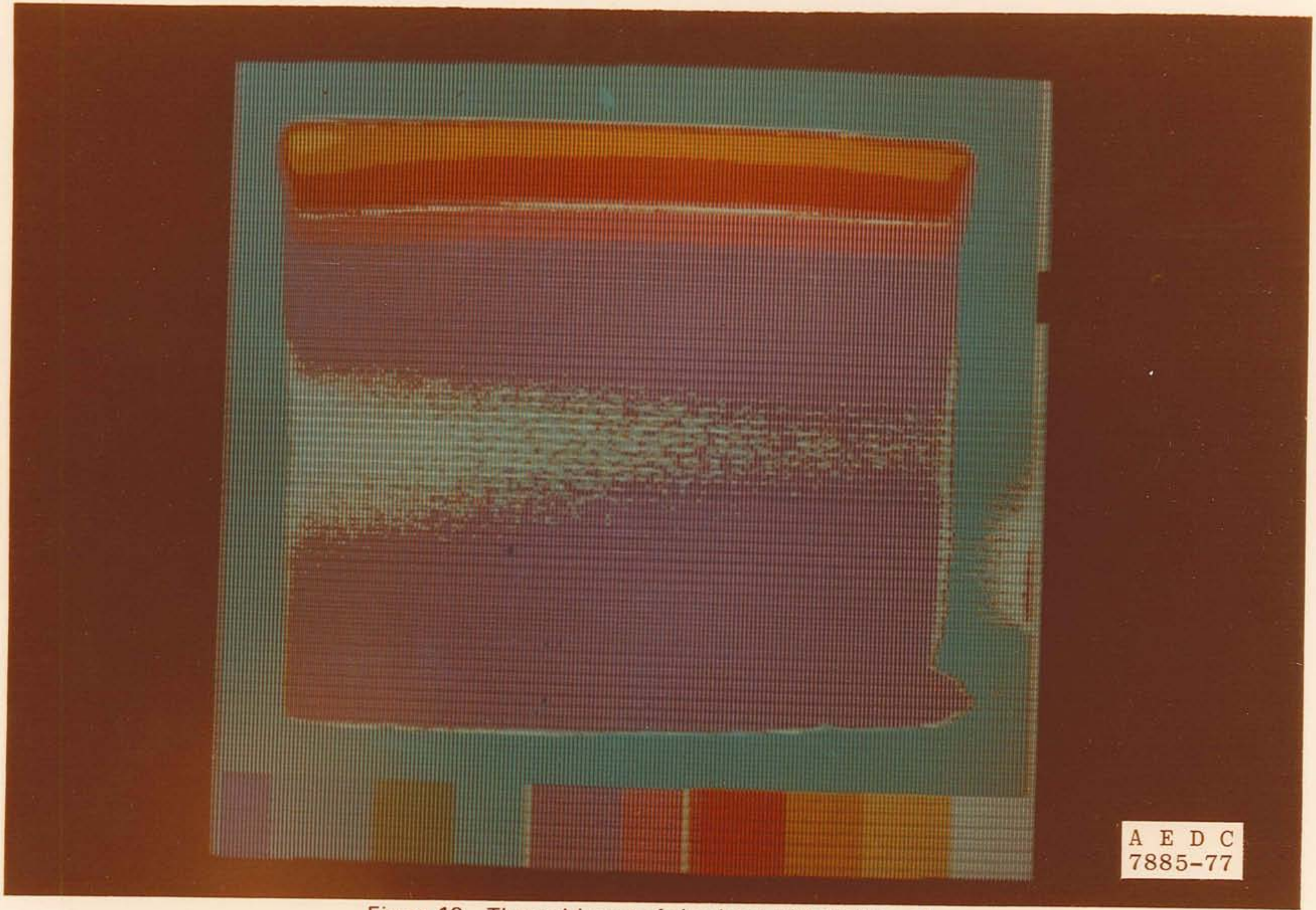


Figure 18. Thermal image of simulator with isothermal contours set at ΔT = 30°C.

APPENDIX A
EARTH-LIMB HEAT TRANSFER FOR CONTROLLED TEMPERATURE DISTRIBUTION OF A RADIATING SURFACE IN VACUUM

For a plate radiating on two sides and with the edges insulated, the heat equation can include variable thickness, t, as follows, assuming one side is flat.

$$K\frac{d}{dx}\left[bt(x)\frac{dT}{dx}\right] = \underline{\sigma\ \varepsilon\ b}\left(T^4 - T_s{}^4\right)\left(1 + \frac{1}{\cos\theta}\right)$$

$$Kbt(x)\frac{dT}{dx^2} + Kb\frac{dt(x)}{dx}\ \frac{dT}{dx} = \frac{\sigma\ \varepsilon\ b}{\cos\theta}\ T_s{}^4\left[\left(\frac{T}{T_s}\right)^4 - 1\right]\left(1 + \frac{1}{\cos\theta}\right)$$

$$\frac{d^2T}{dx^2} = \frac{(1 + \sec\theta)\sigma\ \varepsilon\ T_s{}^4}{Kt}\left[\left(\frac{T}{T_s}\right)^4 - 1\right] - \frac{1}{t}\frac{dt(x)}{dx}\ \frac{dT}{dx}$$

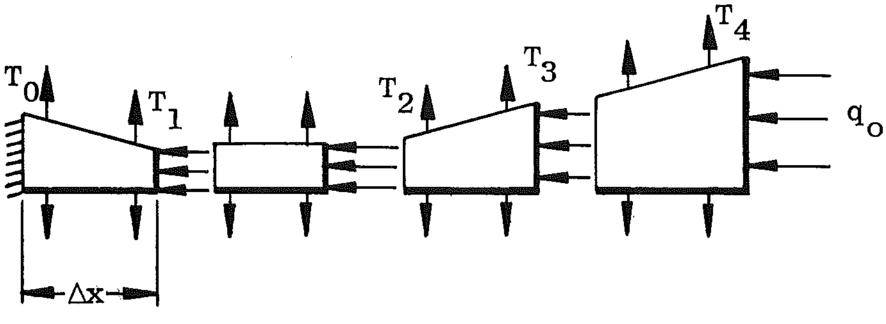
where θ = slope of the plate contour side

$= \tan^{-1} dt/dx$

Using the Runge-Kutta integration technique and initial conditions x 20, $T = T_o$, $dT/dx = 0$, $t = t_o$, and $dt/dx = dt_o/dx$.

A program has been established using the HP 9872 computer for temperature along the plate with any given T_o, T_s, t, and dt/dx.

Where temperature is given along the plate and thickness of plate required, a Simpson's rule integration of total heat can be used as follows



Assume small increments of plate, Δx, and variable thickness t.

$$t_1 = \frac{\sigma\ \varepsilon\ \overline{\Delta x}^2\ T_s{}^4}{2\ K\ \Delta T}\left[\left(\frac{T_o \qquad T_1}{T_s}\right)^4 - 1\right]\ (1 + \frac{}{\cos\theta})$$

$$\theta = \tan^{-1} \frac{t_o - t_1}{\Delta x}$$

Then

$$t_n = \sum_{1}^{n} \frac{\sigma\ \varepsilon\ \overline{\Delta x}^2}{K\ \Delta T}\ T_s^{\ 4} \left[\left(\frac{T_n + T_{n+1}}{2\ T_s}\right)^4 - 1\right]\left(1 + \sec \tan^{-1}\left(\frac{t_n - t_{n-1}}{\Delta x}\right)\right)$$

$$+ \frac{\sigma\ \varepsilon\ \overline{\Delta x}^2}{2\ K\ \Delta T}\ T_s^{\ 4} \left[\left(\frac{T_n + T_{n-1}}{2T_s}\right)^4 - 1\right]\left[1 + \sec \tan^{-1}\left(\frac{t_n - t_{n-1}}{\Delta x}\right)\right]$$

Units: Δx = in. σ = Btu/ft^2/°R K = Btu/ft

$$t_n = \sum_{1}^{n} \frac{\sigma\ \varepsilon\ \overline{\Delta x}^2\ T_s^{\ 4}}{12\ K(T_n - T_{n-1})} \left[\left(\frac{T_n + T_{n-1}}{2\ T_s}\right)^4 - 1\right]\left[1 - \sec \tan^{-1}\left(\frac{t_n - y_{n-1}}{\Delta x}\right)\right]$$

$$+ \frac{\sigma\ \varepsilon\ \overline{\Delta x}^2\ T_s^{\ 4}}{12\ K(T_n - T_{n-1})} \left[\left(\frac{T_n + T_{n-1}}{2\ T_s}\right)^4 - 1\right]\ 1 - \sec \tan^{-1}\left[\left(\frac{t_n - t_{n-1}}{\Delta x}\right)\right]$$

Using curve fit equations for temperature and assuming parabolic form for points near zero slope to expedite and simplify the curve fit.

$$T' = \frac{T}{x}\Bigg|_{\Delta T \to 0} = \frac{dT}{dx}$$

and

$$t_n = \sum_{1}^{n} \frac{\sigma\ \varepsilon\ \Delta x\ T_s^{\ 4}}{12\ K\ T'} \left[\left(\frac{T_n + T_{n-1}}{2T_s}\right)^4 - 1\right] (1 + \sec\ \theta)$$

$$+ \frac{\sigma\ \varepsilon\ \Delta s\ T_s^{\ 4}}{24\ K\ T'} \left(\frac{T_n + T_{n-1}}{2T_s}\right) (1 + \sec\ \theta)$$

where

$$t_n = \text{material thickness at } T_n$$

and

$$\theta = \tan^{-1} dt/dx = \tan^{-1} \frac{t_n - t_{n-1}}{\Delta x}$$

θ is assumed to be zero for starting the integration scheme and hold zero until t/x was significant to avoid the dilemma at small values of T'. Also, the parabolic form of curve fit for small values of T' was matched in T and T' at x = 1 given by best curve fit. Then from the parabola

$$T_{x=1} = KX^n$$

$$K = T_{x=1}$$

and

$$T' = nKX^{n-1}$$

$$n = T'/T\Big|_{x=1}$$

$$T = T_{x=,}\ x^{\left(T'/T\big|_{x=1}\right)}$$